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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Patent Application of

KLEIN et al. Atty. Ref.: 540-556

Serial No. 10/523,713 TC/A.U.: 2817

Filed: February 7, 2005 Examiner:

For: WAVEFORM LINEARISER

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September 8, 2005

Commissioner for Patents
P.O. Box 1450
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Office of Initial Patent Examinations
Filing Receipt Corrections

Sir:

REQUEST FOR CORRECTION OF FILING RECEIPT

Enclosed is a copy of the Filing Receipt for the above-identified application which incorrectly states the first inventor's residence as Hertfirdshire, United Kingdom. It should read Hertfordshire, United Kingdom. The correction is shown in red on the attached copy of the filing receipt. Issuance of a Corrected Filing Receipt is respectfully requested.

Respectfully submitted,

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CONFIRMATION NO. 8391

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ARLINGTON, VA 22203

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Date Mailed: 08/30/2005

Receipt is acknowledged of this regular Patent Application. It will be considered in its order and you will be notified as to the results of the examination. Be sure to provide the U.S. APPLICATION NUMBER, FILING DATE, NAME OF APPLICANT, and TITLE OF INVENTION when inquiring about this application. Fees transmitted by check or draft are subject to collection. Please verify the accuracy of the data presented on this receipt. **If an error is noted on this Filing Receipt, please mail to the Commissioner for Patents P.O. Box 1450 Alexandria Va 22313-1450. Please provide a copy of this Filing Receipt with the changes noted thereon. If you received a "Notice to File Missing Parts" for this application, please submit any corrections to this Filing Receipt with your reply to the Notice. When the USPTO processes the reply to the Notice, the USPTO will generate another Filing Receipt incorporating the requested corrections (if appropriate).**

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Power of Attorney: The patent practitioners associated with Customer Number 23117.

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Title

Waveform lineariser

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Sir:

INFORMATION DISCLOSURE STATEMENT

As suggested by 37 C.F.R. 1.97, the undersigned attorney brings to the attention of the Patent and Trademark Office the reference listed on the attached form PTO-1449.

☒ All listed documents are attached.

☐ Copies of U.S. Patent Publications are not required and are not attached.

☐ Listed foreign patent publications and other documents are enclosed.

☐ The listed documents were cited in the ISR and copies should have been supplied by WIPO directly to the US PTO. If copies are not timely received from WIPO, please telephone the undersigned so that copies can be timely supplied for the Examiner's consideration in this US National Phase Application.

This is not to be construed as a representation that a search has been made or that no better prior art exists, or that a reference is relevant merely because cited.

The Examiner is requested to initial the attached form PTO/SB/08a and to return a copy of the initialed document to the undersigned as an indication that the attached reference has been considered and made of record.

Respectfully submitted,

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PTO/SB/08a

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(Use several sheets if necessary)	540-556	10/523,713
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U.S. PATENT DOCUMENTS

*EXAMINER INITIAL		DOCUMENT NUMBER	DATE	NAME	CLASS	SUBCLASS	FILING DATE IF APPROPRIATE

FOREIGN PATENT DOCUMENTS

		DOCUMENT	DATE	COUNTRY	CLASS	SUBCLASS	TRANSLATION YES	NO

OTHER DOCUMENTS (including Author, Title, Date, Pertinent pages, etc.)

		B. Goldberg, "Linear Frequency Modulation – Theory and Practice" *RF Design*, Sept. 1993, pages 39-46.

*Examiner		Date Considered	

Examiner: Initial if reference considered, whether or not citation is in conformance with MPEP 609; Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to application.

Linear Frequency Modulation — Theory and Practice

By Bar-Giora Goldberg
Sciteq Electronics, Inc.

This article addresses high-performance applications for chirp waveforms, and describes the Sciteq DCP-1, an all-digital mechanism for generating chirp signals with a combination of linearity and operating bandwidth not previously achieved.

A linear frequency modulation (FM) signal, or "chirp" is a swept frequency change over some frequency range. Ideally, the rate of change is perfectly constant (time vs. frequency), without ambiguity or anomaly. Originally stimulated by emerging radar requirements to distribute energy across a range of frequencies, virtually all early LFM signals were generated with analog devices such as a voltage controlled oscillator (VCO) or surface acoustic wave (SAW) resonator. Analog ambiguities were introduced by typical RF component and environment uncertainties, and therefore system performance was far from theoretical, but designers had no choice but to attempt to work around these problems. The cost of linearizing and compensating such circuitry in some cases was as expensive as the rest of the RF subsystem, so the high cost of approaching theoretical numbers, and the unavoidable errors caused by analog solutions, made such applications useful primarily for experimentation and scientific exploration.

The advantage of a chirp waveform drove its adoption by certain high performance radar, sonar, and communication systems, particularly in military systems. A chirp signal's energy is spread across a wide band rather than focused at one point, which helps reduce emitter spectral density and makes it harder to jam. Such an approach permits communication or system operation to continue even if part of the spectrum is blocked. Most importantly, it allows high resolution and is therefore applicable to imaging, altimetry, and fuzing where resolution is an important parameter.

In the late 40s and early 50s, as pulse radar technology grew out of its infancy, a problem became visible. Radar range depends on E/N_0, where E is the pulse energy, $E = P \cdot T$, (P is the received power proportional to the transmit power, T is the pulse duration) and N_0 is the receiver noise density. Resolution depends on the signal bandwidth. These two requirements are related diagonally; improving E makes it necessary to increase T but an increase in T reduces the pulse bandwidth and therefore resolution. The most visible solution was to modulate the pulse, which makes the pulse bandwidth dependent upon the modulating waveform rather than the pulse length of (approximately) 1/T. One of the early waveforms suggested for this application was linear FM, and it remains optimum for many radar applications.

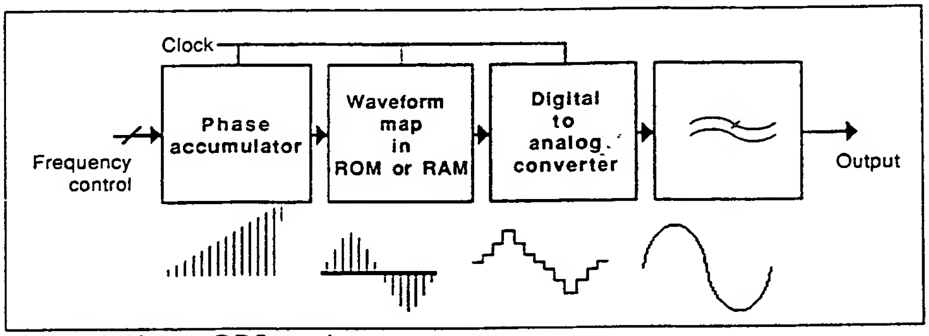

Figure 1. How a DDS works.

Recently, the utility of linear FM in non-radar applications has been recognized. Use of this technique was explored in various other systems including communication, semiconductor process control, sonar, seekers, simulation, and test equipment. In 1989, Sciteq began work on an all-digital technique for producing such systems that would exploit the firm's experience with direct digital synthesis (DDS) technology. DDS (Figure 1) had evolved into a useful signal generation tool, but existing implementations were not appropriate for chirp generation, except at near-audio frequencies for sonar, due to latencies in the designs. Nevertheless, it was clear that the best approach to an idealized chirp generator would exploit some derivative of DDS techniques.

By 1990, key digital and data conversion components had already been developed or were being developed, either by Sciteq or other agencies (Sandia National Laboratories, for one), and for the first time it appeared possible to produce the industry's first wideband digital chirp synthesizer. Accordingly, Army Research Laboratory (then Harry Diamond Labs), let a Small Business Innovative Research (SBIR) Phase I contract to Sciteq to determine the practicality of meeting theoretical goals for the Army's next-generation battlefield surveillance radars. Specifically, the group working on Synthetic Aperture Radar believed that a digital signal generation solution was important to program objectives. Sciteq's interface to this program has been Barry Scheiner of ARL.

The Phase I report was positive and defined a practical path to the desired goal, leading to a Phase II contract award. Though most SBIR projects are considered high risk, the development was successful and first prototypes were delivered during the past year to the Army and to other agencies interested in the exploitation of ideal linear FM signals. The nature of the SBIR program is to permit the contractor to retain control over the new technology, and to commercialize the results where possible, hence the availability of Sciteq's direct-digital chirp synthesizer (DDCS) to the industry. That product, designated the DCP-1, is a DDCS that produces linear FM signals over a band of more than 230 MHz, with linearity approaching an

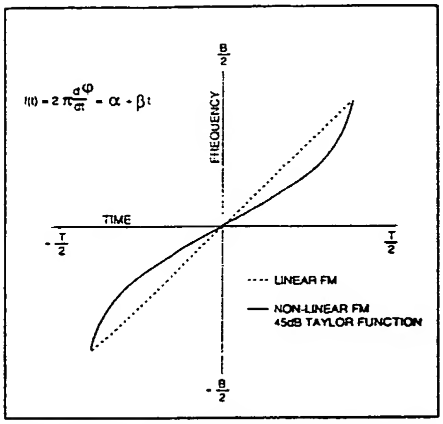

Figure 2. Frequency-time laws for typical linear and non-linear chirp signals.

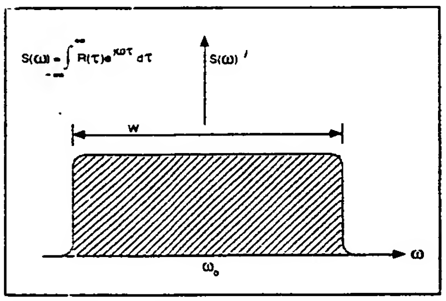

Figure 3. Chirp signal spectrum for W·T>>1.

ideal level previously defined only by mathematics and never actually observed.

Waveform Properties

A substantial amount of theoretical work was done to calculate the properties of such signals, i.e., power spectrum, auto-correlation, etc., and the characteristics of that theoretically perfect LFM signal were defined.

A general description of such a signal is given by:

$$s(t) = A \cdot \sin\left(\alpha t + \frac{\beta}{2} t^2 + \varphi_0\right)$$

and some of its properties are shown in Figure 2.

If the signal bandwidth is designated as W, then the product, W·T = TB, the time bandwidth product for radar applications or processing gain for spread spectrum communications.

For W·T = TB >> 1,, the power spectrum is flat (Figure 3) and the signal energy is distributed almost equally across the bandwidth, W. The signal auto-correlation is given by:

$$R(\tau) = \left(\frac{\sin X}{X}\right)^2$$

where,

$$X = \pi \cdot \tau \cdot W = \pi \cdot \tau \cdot \frac{TB}{T}$$

It can be shown that the signal auto-correlation has relatively high sidelobes with the worst case of –13.5 dB (approximately 20log [sin X/X] for X = 1.5π); see Figure 4. This parameter can be improved by adding the complexity of either amplitude modulation or phase modulation (pulse weighting), and there is an extensive body of literature on this issue. Unfortunately, while there is a great deal of mathematical extrapolation from ideal data, the experimental results were derived from analog mechanisms and therefore were limiting.

Applications

LFM is extensively used for both pulse Doppler radars and synthetic aperture imaging radars. As always, the more linear the LFM signal the better the performance of the system, but even the relatively crude chirps generated by analog circuitry are better than non-chirped operation. With the advent of DDCS technology, with its inherent deterministic linearity, resolution of SAR and performance of other chirp-dependent systems is improved.

In range measurement systems, for altimeters, control, flight control, etc., the principle and the advantages of digital LFM are shown in Figure 5.

Compressive receivers are used to scan the spectrum, and unlike typical spectrum analyzers, which sweep the spectrum and find *all* signals that are within the analyzer bandwidth (during the time of the sweep only), these receivers see all signals that occur within the sweep time. In this respect, a compressive receiver operates like a real time DFT analyzer. An ideal compressive receiver depends upon a linear and fast chirp over the desired band of reception.

In semiconductor production, wafer perfection is a critical issue that influences yield, and therefore has serious economic impact. Surface anomalies and contamination are usually detected using a laser technique, where the laser is reflected off the wafer surface and scatter characteristics evaluated to determine surface characteristics,

resulting in a map of the wafer showing imperfections, contamination, and therefore usable dice. In most such applications, the wafer is moved mechanically, and the laser is modulated by a Bragg cell driven by a linear FM signal (produced from an expensively-compensated VCO). The linearity of the FM signal is one of the factors that determines resolution of the system, and also affects the "guard" area around imperfections that are detected. The more accurate the signal, (hence, the more deterministic the laser position), the smaller the guard area and the higher the yield.

Digital LFM Synthesis

Evolution of digital technology has allowed certain Direct Digital Synthesizer (DDS) implementations to operate at sufficient speed to produce bandwidths sufficient for the above applications.

The use of DDS disciplines bring with it cardinal improvements in the waveform features such as:

- The signal is synthesized and therefore every pulse is identical.
- The chirp linearity approaches the limits of measurement.
- Phase manipulation is digitally accurate and is available at almost no additional cost.
- Control of parameters such as start frequency, stop frequency, chirp rate, on/off, are deterministic and accurate.

The basis of the digital implementation

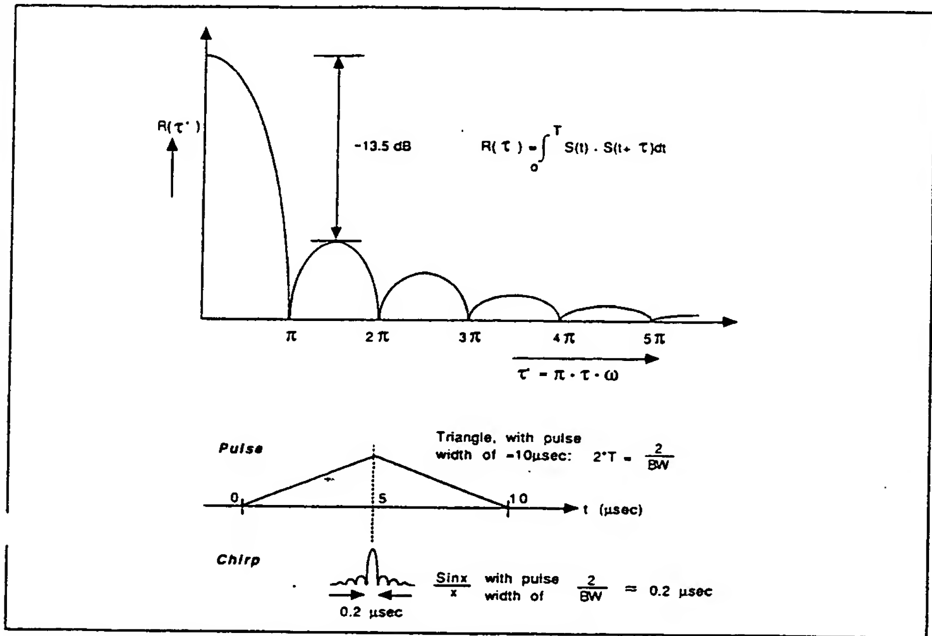

Figure 4. Auto-correlation function as sin X/X.

is shown in Figure 6. The output of this digital process can be represented as:

$$s(t) = \sin\left(\frac{\beta \cdot t^2}{2} + \alpha \cdot t + \varphi_0\right)$$

The general structure is that of a dual accumulator. Since an accumulator is a discrete integrator and we need to generate a quadratic function, two accumulators are necessary.

The output of the first accumulator is the instantaneous frequency and the frequency adder allows the setting of a start frequency. The F output allows the monitoring of the instantaneous frequeny. The input of the first accumulator is therefore β in the equation and the frequency input is α. The output of the second accumulator is the signal's phase and therefore can be phase modulated by another adder. This input is equivalent to the term, φ_0, in the equation.

Such structure can be implemented in

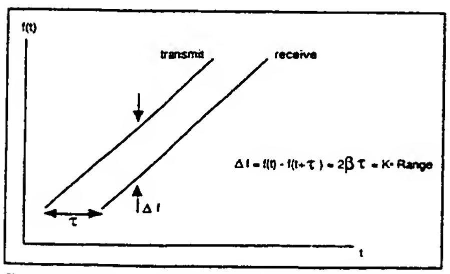

Figure 5. Range meaurement using linear-FM.

CMOS technology at clock frequencies up to 100 MHz, and in high speed ECL and GaAs technologies up to 800 MHz, though it must be remembered that the nature of a DDS allows an output frequency of less than half the clock.

In the block diagram, the chirp chip and phase adder (implemented in one device) are followed by a SINE ROM, a DAC (digital to analog converter), and a low pass filter. Because of the nature of the output spectrum (sin X/X) and the group delay of the filter, amplitude and group delay equalization improves the result.

Practical Implementation: the DCP-1

The Sciteq model DCP-1 is an all-GaAs direct-digital chirp synthesizer (DDCS) clocked at 500 MHz and therefore generating output frequencies from DC to 230 MHz (limited by Nyquist and the low pass filter considerations). Though the design involves several support functions, the basic chirp generation function is achieved by three devices, a double-accumulator, a memory, and a digital-to-analog converter.

In the double accumulator, both accumulators are 24 bits in size, thus yielding a minimum step size of ≈29.8 Hz. The frequency and phase accumulator functions are integrated into one device, developed by a Sandia National Laboratories program under the leadership of Bruce Walker. The part includes not

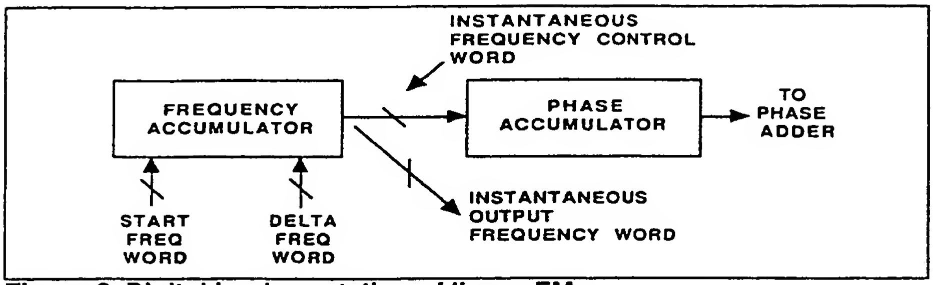

Figure 6. Digital implementation of linear-FM.

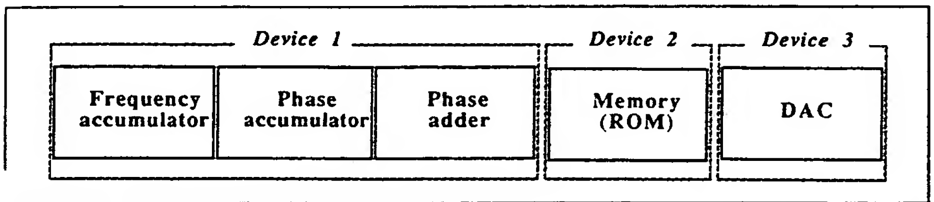

Figure 7. Basic architecture of the DCP-1.

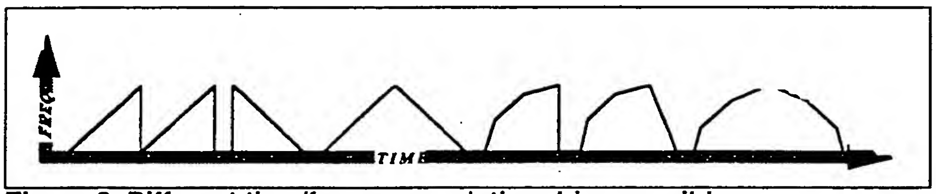

Figure 8. Different time/frequency relationships possible.

only the specified accumulation functions, but also provides 12 bits of phase control plus a time-equalized 8-bit frequency output that supports system timing. The memory device uses a patent-pending algorithm (Sciteq's) to map the phase output of the accumulator to digitally-defined amplitudes, also at a 500 MHz rate or better. The digital output of the memory is considered near-perfect, 'th digital error supporting a spurious ˌsponse better than 70 dB below the carrier, so it is the digital-to-analog converter (DAC) that limits the spectral purity of the system. In the initial DCP-1s, the DAC is a 12-bit GaAs part developed by a consortium including GE, Sciteq, Motorola, and Hughes. The DCP-1 basic architecture is shown in Figure 7.

In the LFM mode, the DCP-1 updates frequency at a 500 MHz rate, which means that a new frequency is synthesized every two nanoseconds. The slowest chirp rate is ≈15 kHz/µsec (≈30 Hz times 500, since there are 500 steps in each microsecond). For a full band sweep, this would take approximately 13.4 msec (230,000,000 ÷ 29.8 2 nsec = 15.4 msec). Obviously, faster sweeps are possible and are only limited by the resolution that is acceptable (as an extreme, at 230 MHz resolution it's one full chirp — a single step in two nanoseconds). A chirp rate of 10 MHz/µsec is practical if it is desired to cover a 50 MHz bandwidth in 5 µsec (5 µsec ÷ 2 nsec for the number of steps gives a required resolution of 20 kHz).

The synthesizer is controlled by loading two registers — start frequency and chirp rate (or step size). When the chirp begins, the step size will be added to the start frequency every 2 nsec. At any point during the chirp it is possible to change the chirp rate so that the different time:frequency relationships shown in Figure 8 are possible. A negative value in the chirp rate register will produce a sweep starting at a higher frequency and moving lower, thus supporting complete manipulation of all parameters of the output.

In addition, 12 bits of phase control are available for compensation of the response during the sweep to reduce side lobes. This may be updated at a rate limited only by speed limitations of TTL logic. Phase control adds another dimension of flexibility by permitting the control of phase from pulse to pulse, which permits accurate matching of signals.

Basic specifications for the DCP-1 are given in Table 1.

Subsystem Configurations

The DCP-1 is shipped in a conventional 5.25 in. chassis that includes the basic chirp synthesizer (designated the DCP-1A) and the support functions shown in Figure 7. Users are encouraged to begin work with the complete system, as shown, to reduce risk and speed integration time. In production, however, some combination of the power supply, output filter, control interface, reference, and cooling blocks will ordinarily be integrated into the user's system. Production systems therefore use only the basic DCP-1A module (about 5"×7"×1").

Applications and Experimental Results to Date

The DCP-1 generates its output in the low-UHF range. Typically, that chirp signal must be upconverted to the desired system operating range by either mix/filter or multiplication techniques. The DCP-1 is now used by a variety of systems, including two millimeter-wave seeker programs, four synthetic aper-

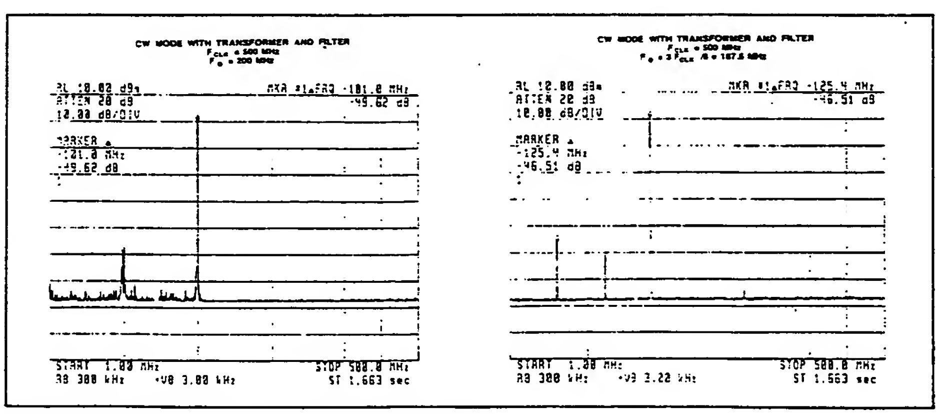

Figure 9. Spurious performance plots.

Parameter	Specification
Maximum Clock	500 MHz
Maximum Output Frequency	≈230 MHz
Frequency Resolution	24 bits (~29.8 Hz)
Frequency Update Rate (Sweep mode)	2 ns
Output Power	0 dBm ±1.5 dB
VSWR	<2.0:1
Harmonics (CW)	–45 dBc
Spurious (CW)	–50 dBc, typical
Phase Noise (CW)	
10 Hz offset	–80 dBc/Hz
100 Hz offset	–95 dBc/Hz
1 kHz offset	–110 dBc/Hz
10 kHz offset	–120 dBc/Hz
100 kHz offset	–130 dBc/Hz
1 MHz offset	–140 dBc/Hz
Group Delay Variation	
DC to 100 MHz	<0.5 nsec
DC to 150 MHz	<1 nsec
DC to 230 MHz	<4 nsec
Phase Modulation	12 binary bits
Power (DCP-1 chassis)	28VDC, 1.6A
Power (DCP-1A module)	–5.2VDC, 2.5A
	–2VDC, 500mA
	+5VDC, 100mA
	–12VDC, 125mA

Table 1. DCP-1 specifications.

ture radar systems, one electronic warfare program, and (in baseband) at least one wafer process control system.

So far, system developers have reported very favorable results. Spurious signal level was initially a concern, but one unpredicted result of experimentation is that discrete spurious signals seem to be integrated into the general output, and have little result on overall performance. Figure 9 shows typical spurious plots.

Linearity is within quantization levels, therefore for broadband chirps the errors are smaller than measurement techniques can detect. Initially, repeatability was evaluated using the configuration shown in Figure 10. The output of the DCP-1 was delayed and then compared with itself, and the result measured on an HP 3561A FFT analyzer.

Linearity testing was conducted using the Racal-Dana 2351 Time Interval Analyzer and the HP 5373A Modulation Domain Analyzer. The results are shown as Figure 11, which includes both time vs. frequency data and a histogram displaying frequency distribution.

First users report that controllability is a potential issue due to the speeds involved. Therefore, an interface card was developed to speed initial integration and provide a benchmark to support design of the user system's interface to the DCP-1.

Most users require that the DCP-1 be eventually reduced in size, price, and power consumption. At least one high-volume program requires the basic UHF chirp signal generation to be accomplished on a hybrid of about one square inch. Power consumption is a function of the digital process, and new devices are now being considered to reduce dissipation by about half. As usage/production increase, and the level of integration is improved, costs will improve as well.

The future of the DCP-X (and systems like it) depends upon two factors: yield/cost of digital and data conversion hardware, and performance of data conversion devices. As costs go down and performance improves, digital chirp generation will become a practical solution for more and more categories of systems, in both military and commercial markets. Like spread spectrum, which was once a classified and expensive approach to certain communication requirements, direct-digital chirp synthesis will be exploited in many predictable and also unforeseen niches of the RF industry.

Availability

The DCP-1 and DCP-1A are produced by Sciteq Electronics, Inc., San Diego, CA, tel. 619-292-0500. Availability is 6-8 weeks, at $25k (DCP-1 chassis) and $12.5k (DCP-1A module). *Readers may obtain further information by circling Info/Card #199.* RF

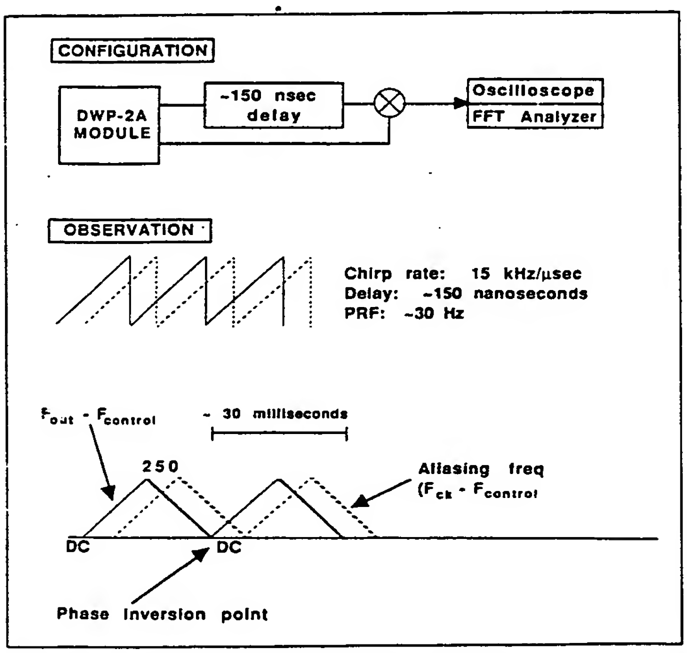

Figure 10. Repeatability testing method.

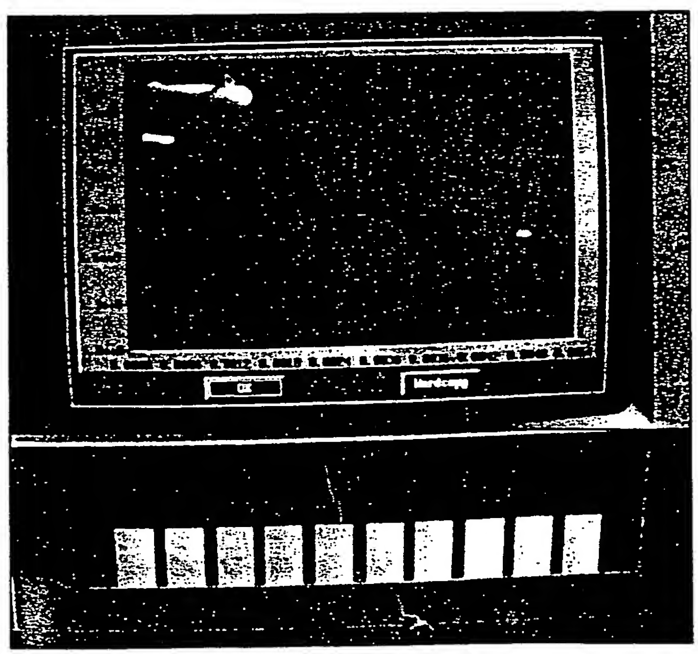

Figure 11. Linearity test results